

**Doc Number: Beams-doc-4867****Version: 2****Category: Notes**

Calibration of BLM Response to Proton Loss

Bruce C. Brown
Main Injector Department, Accelerator Division
*Fermi National Accelerator Laboratory**
P.O. Box 500
Batavia, Illinois 60510

06/30/2015 (rev 3/10/20)

***Operated by the Fermi Research Alliance under contract with the
U.S. Department of Energy.**

Abstract

Protons are lost in the Main Injector at or near the 8 GeV injection energy. This loss has been successfully localized by the collimators to deposit its energy in the MI300 collimator region. We will show that a loss model which assumes protons are lost at the collimator locations and the nearby Beam Loss Monitors (BLM's) provide a response proportional to the number of protons lost. Simulations suggest that 80% of the lost beam power is deposited in the secondary collimators. Additional BLM's in the area respond to the secondary particles but are not required to understand the proton loss. We calibrate these BLM's with the activation of the secondary collimators as measured by the residual radiation on the collimator aisle side. An alternative calibration using the activation of Al tags provides a similar measured sensitivity. An additional consistent calibration is obtained by fitting the weekly loss as measured by the toroids to the weekly sum of the BLM response. This document will refine the loss studies reported in Beams-doc-4519 [1].

I. Introduction

As the Main Injector was transformed to provide high intensity 120 GeV protons for neutrino production in addition to the production of PBars and injection of protons and PBars for the Tevatron Collider program, loss control became a concern. The loss patterns were examined and mitigation tools were developed. An overview is provided in Ref [2]. The beam not captured by the rf system for acceleration is deposited in the Main Injector Collimator system. Anti-damping of beam which has slipped into the gaps intended for extraction prevents those protons from being accelerated and lost during extraction thereby activating the Lambertson magnets at the transfer locations. Eventually, the beam which slipped into the injection gaps was removed by the gap clearing kickers (GCK) but these losses were present during much of the time period for which we are reporting. We will examine the proton intensity injected and extracted from the Main Injector as measured by toroids. We will compare this to the ionization signal recorded in the BLM's in order to calibrate the BLM signal in terms of the protons lost. The BLM data will cover the period beginning in October 2006 when the BLM datalogging began through 30 April 2012 at the end of the running period. A report on this work was submitted to ARIA2015 showing the calibration status in April 2015 [3].

II. Loss Localization

Our ability to determine the relation between the protons lost locally and the global loss determined by the toroids is made possible by the fact that very little beam is lost except during injection, 8 GeV circulation, and initial acceleration ($<1.5\%$ dp/p) so the energy deposited by each proton is about the same. In addition, $>90\%$ of this loss occurs in the collimation region. The secondary collimators have been set to provide the limiting aperture for the beam. The nearby BLM will record a signal proportional to the protons lost on the collimator. The four secondary collimators are sufficiently separated to allow only a little signal from other loss locations to be recorded. We will see that some of the loss at C301 affects both the BLM signal (LI303) and the AI Tag activation measurements at C303. The loss recorded by the BLM at 309 and the activation at C308 were significantly impacted by protons lost at C307 prior to the installation of masks (STCM307A,B) which were installed in the 2009 Facility Shutdown. Using activation measurements we will apportion the lost protons among the BLM's. We find that C301 and C307 losses are accurately reflected by the BLM's signals LI301 and LI307 while the LI303 signal is increased by the C301 loss and the LI309 signal is increased by the C307 loss. The geometric relation between loss monitor and collimator is very similar at 301, 303 and 307 and the responses are quite similar. The LI309 signal due to loss at C308 is not so different but the geometry is completely different (forward and distant rather than backward and nearby) so the similarity in response is accidental. The geometry differences limit detailed understanding.

Secondary Collimator and Mask Installation History

To provide 'markers' for the various changes in beam loss and activation, here is a table of changes:

Table 1: Loss Control History

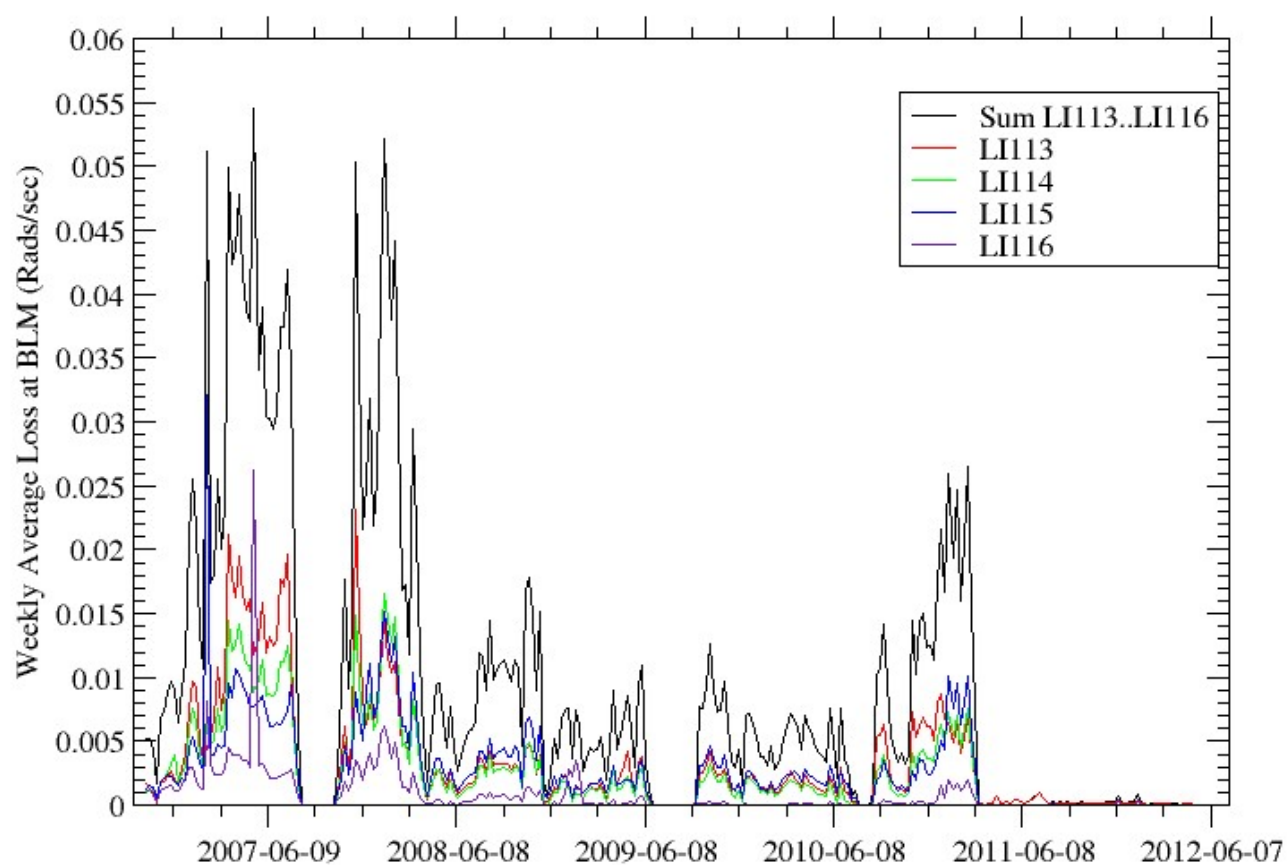
Dates	Subject
10/11/2006	First Data Logged from New BLM Electronics
8/5/2007	Beam off for 2007 Facility Shutdown
	Install Main Injector Collimation System
May - Sep 2008	Commission MI Collimation
4/8/2009	New Horizontal Collimation Orbit
6/13/2009	Beam off for 2009 Facility Shutdown
	Add Masks STCM307A,B downstream of C307
7/17/2010	Beam off for 2010 Facility Shutdown
8/18/2010	Beam on after 2010 Facility Shutdown
	Commission Gap Clearing Kickers
3/07/2011	Replace Faulty Bellows at MI113
9/30/2011	Last Beam for Tevatron, PBar
4/30/2012	Beam off for 2012-13 Facility Shutdown

Before detailed consideration of the BLM calibration, we will examine several features of the loss around the ring so as to understand how local proton loss causes distributed BLM loss signals.

Loss Localization Near Faulty Bellows at MI113

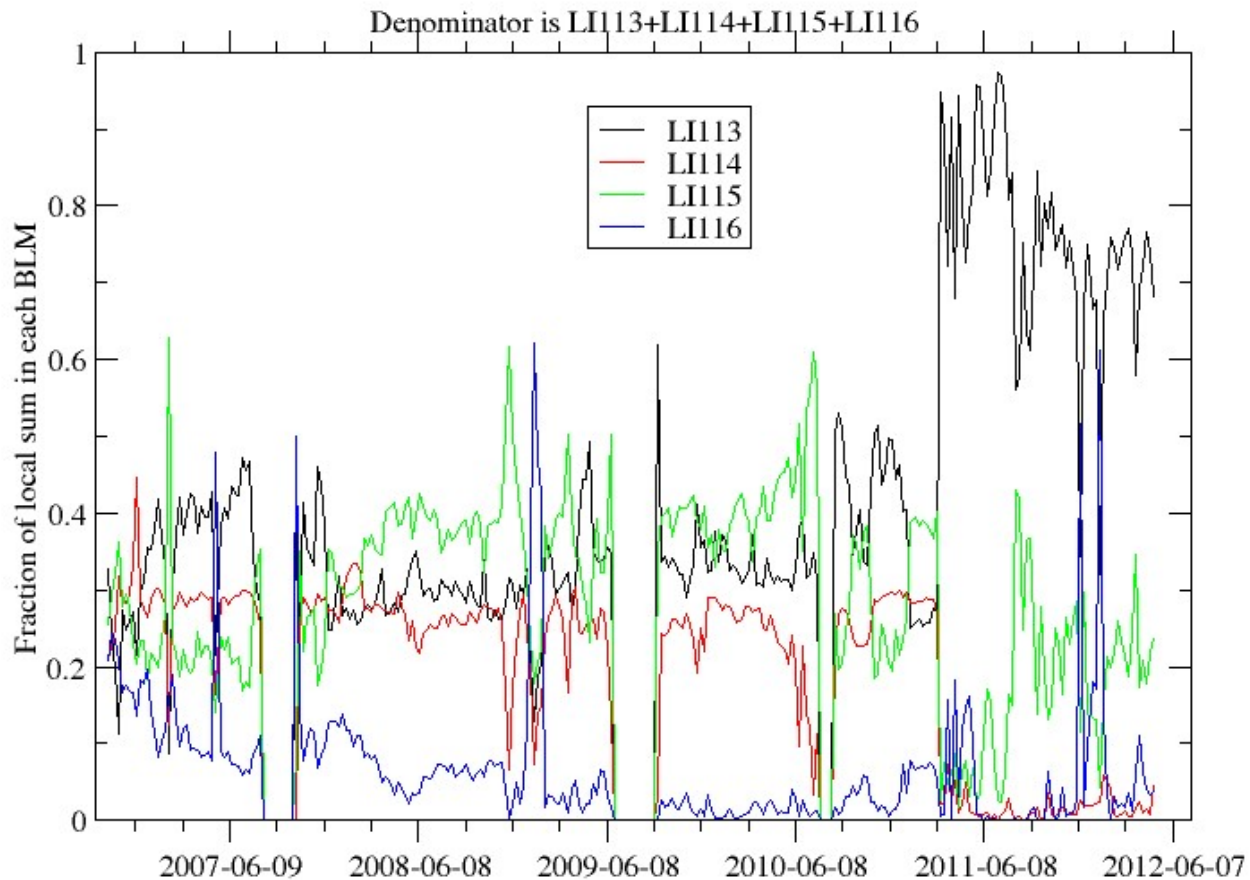
As described in Section V-D of Ref [2], a Main Injector elliptical bellows was mis-installed in 2002 but not replaced until 2011. The resulting loss pattern provides a helpful illustration of the distribution of BLM response to a localized proton loss. As a reminder, we note that each half cell has a BLM placed on the wall at the downstream end of the quadrupole and above beam height. The limited vertical aperture through the faulty bellows was discovered after tuning intensively failed to improve the losses observed on the loss monitors LI113, LI114, and LI115.

Weekly Loss at BLM's from Faulty MI113 Elliptical Bellows



The average weekly loss in this region is shown here. The BLM signal is distributed between the three loss monitors at LI113, LI114 and LI115 with almost no signal at LI116. But all of this is due to protons lost at the faulty MI113 bellows which was just upstream of MI113 dipole D1. This is demonstrated by the fact that the signal goes away when the repair was made in March 2011. Higher loss at this location was the norm until the commissioning of collimation in Spring 2008 when the loss rate dropped by more than a factor of three. The loss rate was permitted to rise again in concert with injection kicker losses when the tunnel work in MI106 area was complete but before the commissioning of the Gap Clearing Kickers. This was because we allowed more loss in the injection region since essential work was completed in the 2010 shutdown and the Gap Clearing Kickers were to be commissioned soon.

Loss Distribution for MI113 Faulty Collimator

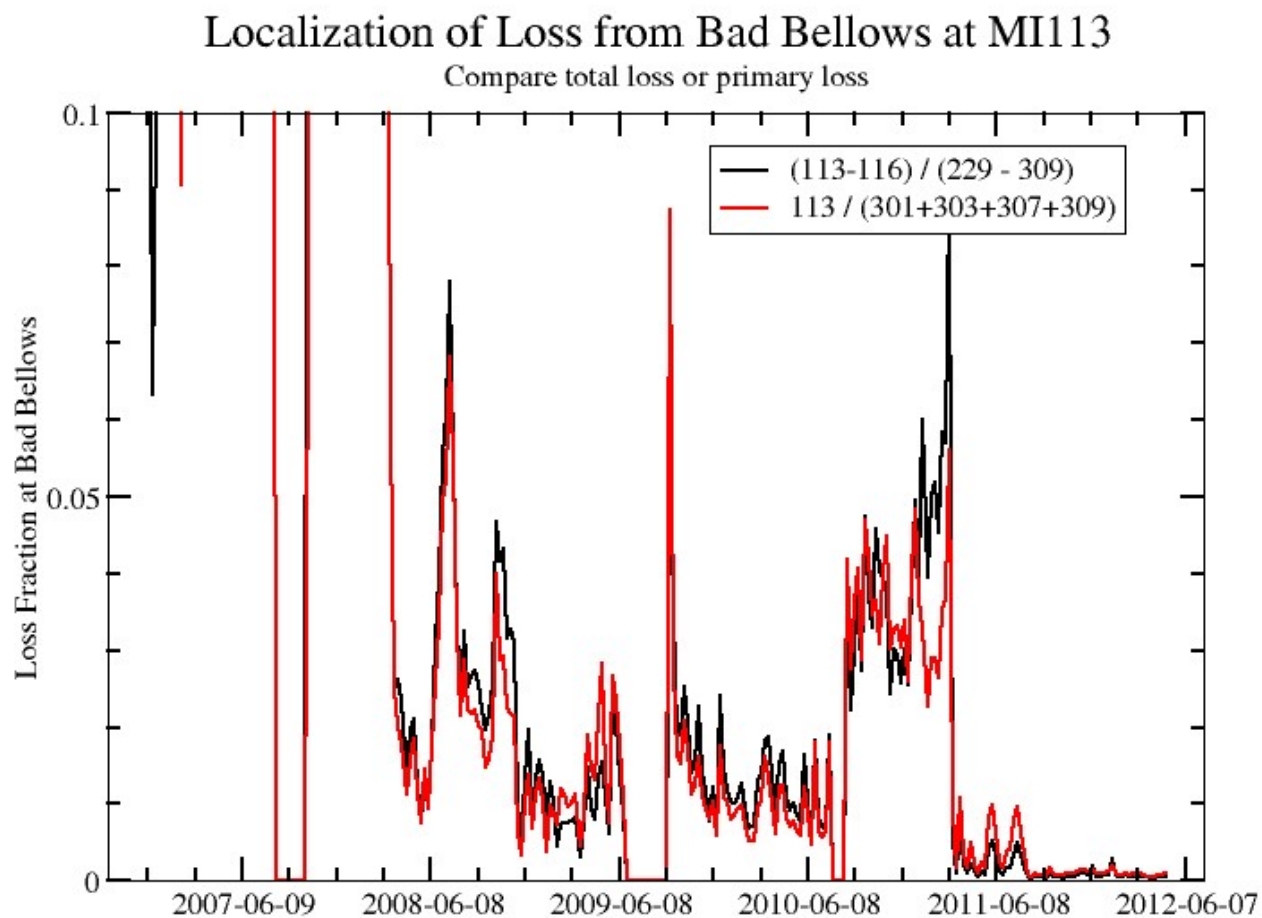


The BLM signals from the protons which struck the errant rf fingers of the MI113 downstream bellows show up in LI113, LI114 and LI115. From Spring 2008 through March 2011, the loss signal at LI115 was a bit larger than that from LI113 and LI114 was typically a bit smaller. Since the whole signal nearly disappears (down by x50) when the bellows was replaced, we can see that much of the loss signal is from secondary particles which are produced in the initial interaction. If the signal in LI115 was primarily from scattered primary protons, we would expect the LI114 signal to be much smaller since it is at a vertically defocusing (minimum vertical size) location. Thus we would describe the LI113 signal as 'signal from primary proton loss'. Let us summarize this result. In doing so, we find an interesting limit to looking at weekly quantities. We show weekly averages of the loss fraction at each of the loss monitors compared with the sum of the four losses but find that they do not sum to one. Comparing the ratios of the loss to the sum is more well behaved as shown in Table 2. The period from 10 Aug 2009 through 9 Aug 2010 will be designated as 'Year 3' of the A1 Tag analysis to be discussed below.

Table 2: Loss Distribution from Bad Bellows at MI113

	Weekly Average	Weekly Average	Period Sum	Period Sum
Begin	10 Aug 2009	9 Aug 2010	10 Aug 2009	9 Aug 2010
End	9 Aug 2010	7 Mar 2011	9 Aug 2010	7 Mar 2011
113/Sum	0.288	0.366	0.331	0.370
114/Sum	0.197	0.254	0.250	0.283
115/Sum	0.352	0.278	0.401	0.301
116/Sum	0.012	0.037	0.017	0.046
Sum of Ratios	0.849	0.935	1.0	1.0

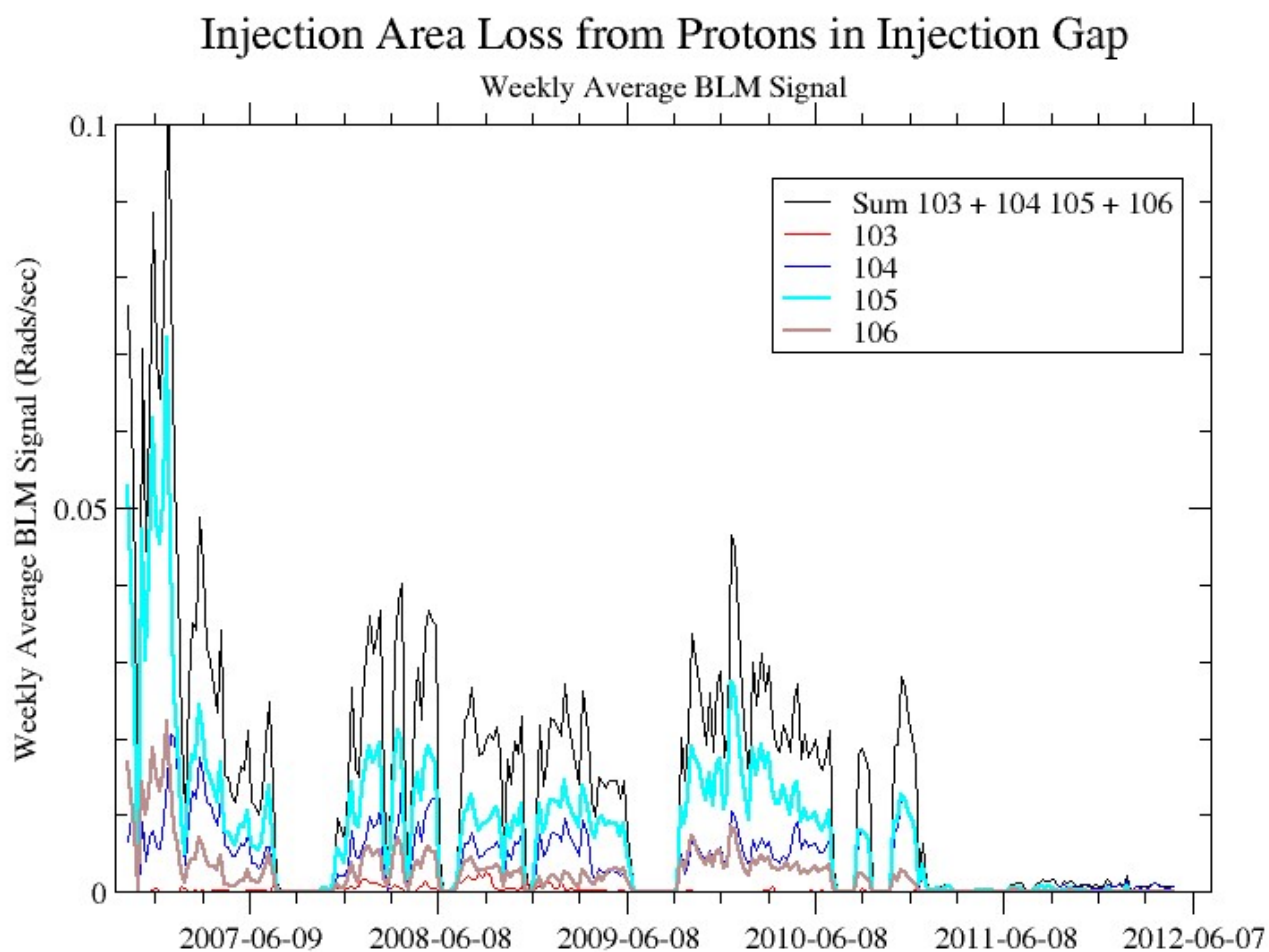
The loss pattern is completely different after the bellows was replaced. The LI113 loss for that last year may be due to injection losses. MI113 is at a phase advance with respect to the K103 injection kicker so that mis-timing or amplitude errors which fail to place all the injection beam on the circulating orbit can deposit proton losses at this location. But remember than this is only about 2% of the previous loss level.



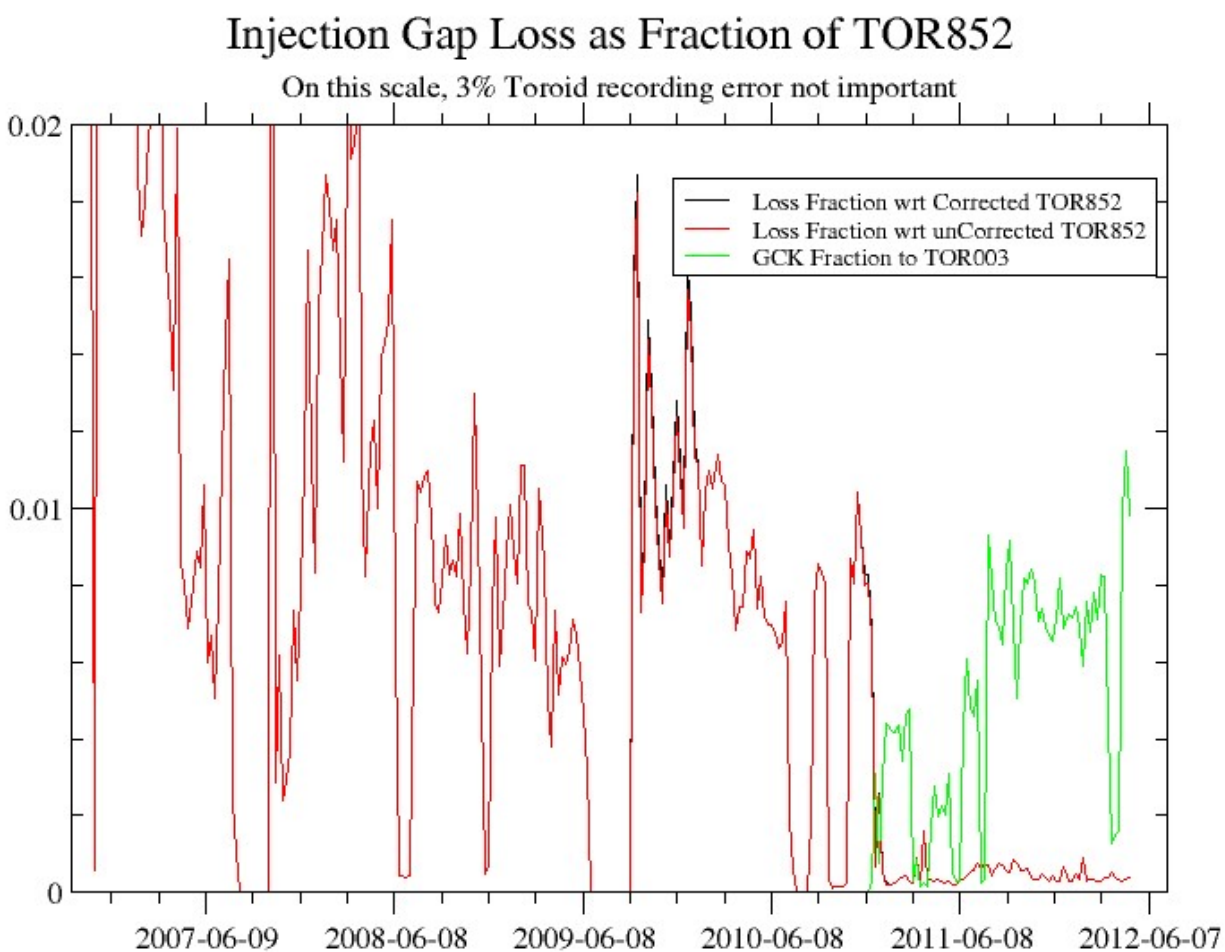
Here we see how much loss occurs at this location. We will show below that after the collimators were commissioned, the collimator region absorbs almost all loss. We can identify the proton loss at the 113 collimator with the LI113 loss similarly to the identification of the collimator proton loss with the loss observed at LI301, LI303, LI307 and LI309. We compare the total loss in LI113..LI116 to the total loss in the collimation region from LI229..LI309. Since this is <2% of the loss in 2009-10 and still <4% when the larger loss occurs after installation but before commissioning of the Gap Clearing Kickers, we will not include this loss in our efforts to calibrate the Collimator BLM system. Note also that if we assume the same sensitivity of the BLM to local proton loss, the ratio of protons lost at LI113 to protons at the four secondary collimators is quite like the ratio for the loss sums. The proton loss location gets about 40% of the total BLM signal while the secondary particles produce the remaining BLM signal.

Localization of Injection Gap Loss / Calibration of LI103-106 BLM's

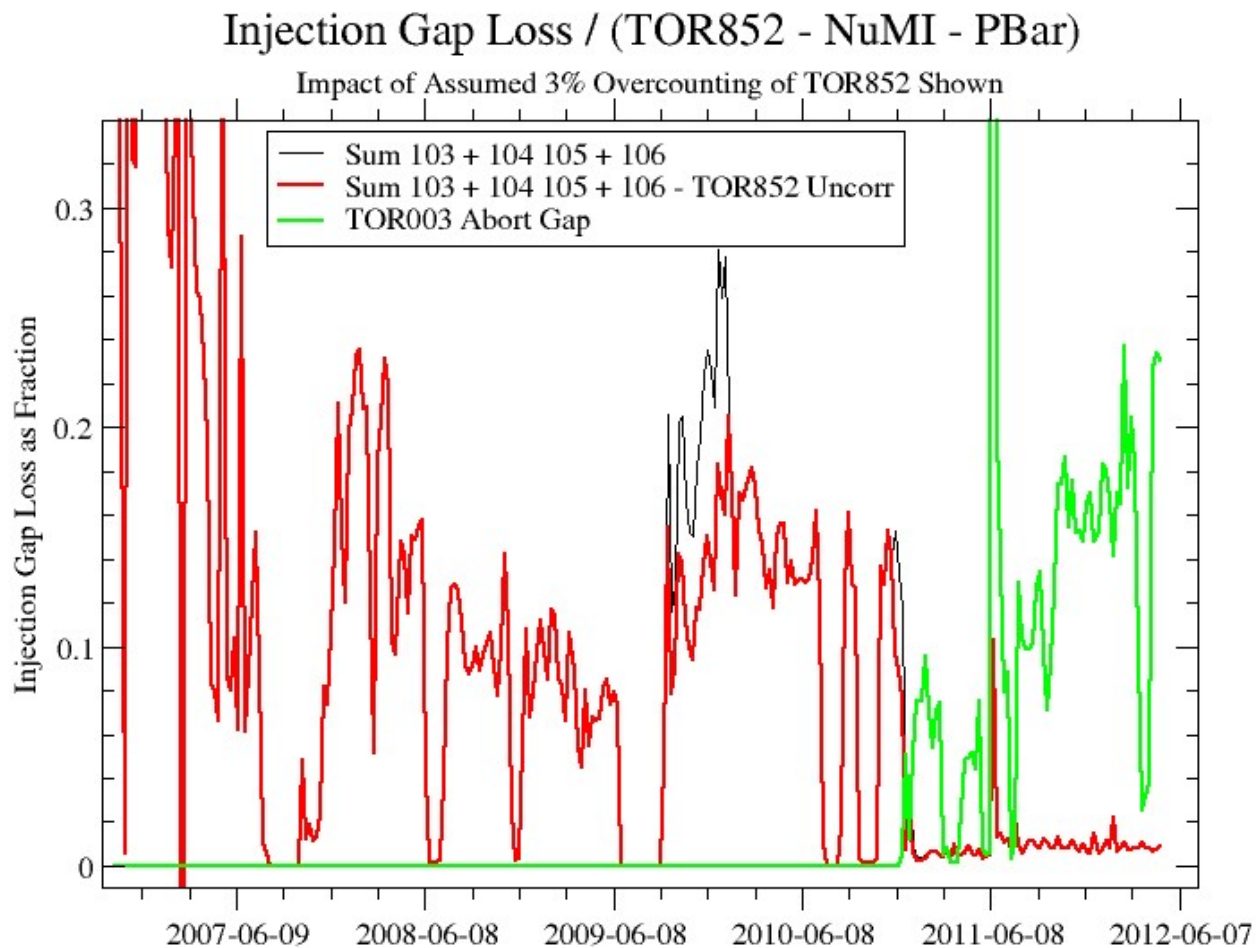
As slip stacking was developed, it was found that the low rf voltage required to hold two different beams created buckets which were unable to contain all of the Booster beam. As a result some beam has slipped into the injection gap before the next injection. This beam was on center vertically whereas the incoming beam required a vertical kick. Circulating beam in the injection gap was kicked and the protons lost in the region from MI104 through MI106. The vertical circulating beam orbit was adjusted to distribute that loss so as to minimize the residual radiation in this region of the tunnel. Injection devices for the planned upgrade to inject beam into the Recycler Ring from the MI8 Line were to be installed in 2010. The Gap Clearing Kickers (GCK) which allows this 'beam-in-gap' to be extracted to the MI Abort were installed in the 2009 shutdown but the power supplies were not available until after the 2010 shutdown. After commissioning of the GCK, TOR003 measured the intensity of the 'beam-in-gap', summing the signal from the separate injections and reporting a per-MI-cycle value. Assuming (knowing, actually) that the gap loss remained rather constant, we can calibrate the integrated loss from LI103 through LI106. The resulting weekly loss sum is shown in the next figures.



Slip stacking of a double batch for PBar production was started in 2005. The increased loss apparent at the beginning of this plot was reduced by a combination of the commissioning of the MI8 Collimation system in early 2007 and by operational loss restrictions. We see the sharp drop in loss to the 103..106 region occurs in the week ending 10 January 2011 due to the commissioning of the Gap Clearing Kicker system. The ratio $(LI103..LI106)/COL$ (BLM sum in collimator region) falls from around 3.5% - 5.5% to 1% in Jan-Sep 2011 and 0.3% in Sep 2011 - Apr 2012. The loss was mostly in LI105 which was 50% - 57% of the local sum.



We will need to know the loss in this region for calibrating the collimation region toroids. Since the beam qualities remained roughly constant, we will compare the BLM sum (LI103..LI106) to the injected beam as measured by TOR852 and recorded by the Beam Budget Monitor (BBM). For normalization of the loss we will examine the beam delivered by the GCK to TOR003 for a three week period 22 August - 12 September 2011 as a fraction of TOR852. For this calibration we used 0.83% of TOR852 (It should have been 0.82%.) Averaging over a 32 week period from Summer 2011 through Spring 2012 we find a ratio of 0.74% (~10% lower). Remember as we move on, however, that the impact is on the fraction of loss rather than the fraction of injected beam so for 94% transmission, the potential change is ~0.1%/6% or 1.67% for the contribution to the collimator loss from Injection Gap loss. After September 2011, the fraction (852 - NuMI - PBar)/852 dropped to about 4.4% but the injection gap loss was then delivered to TOR003.

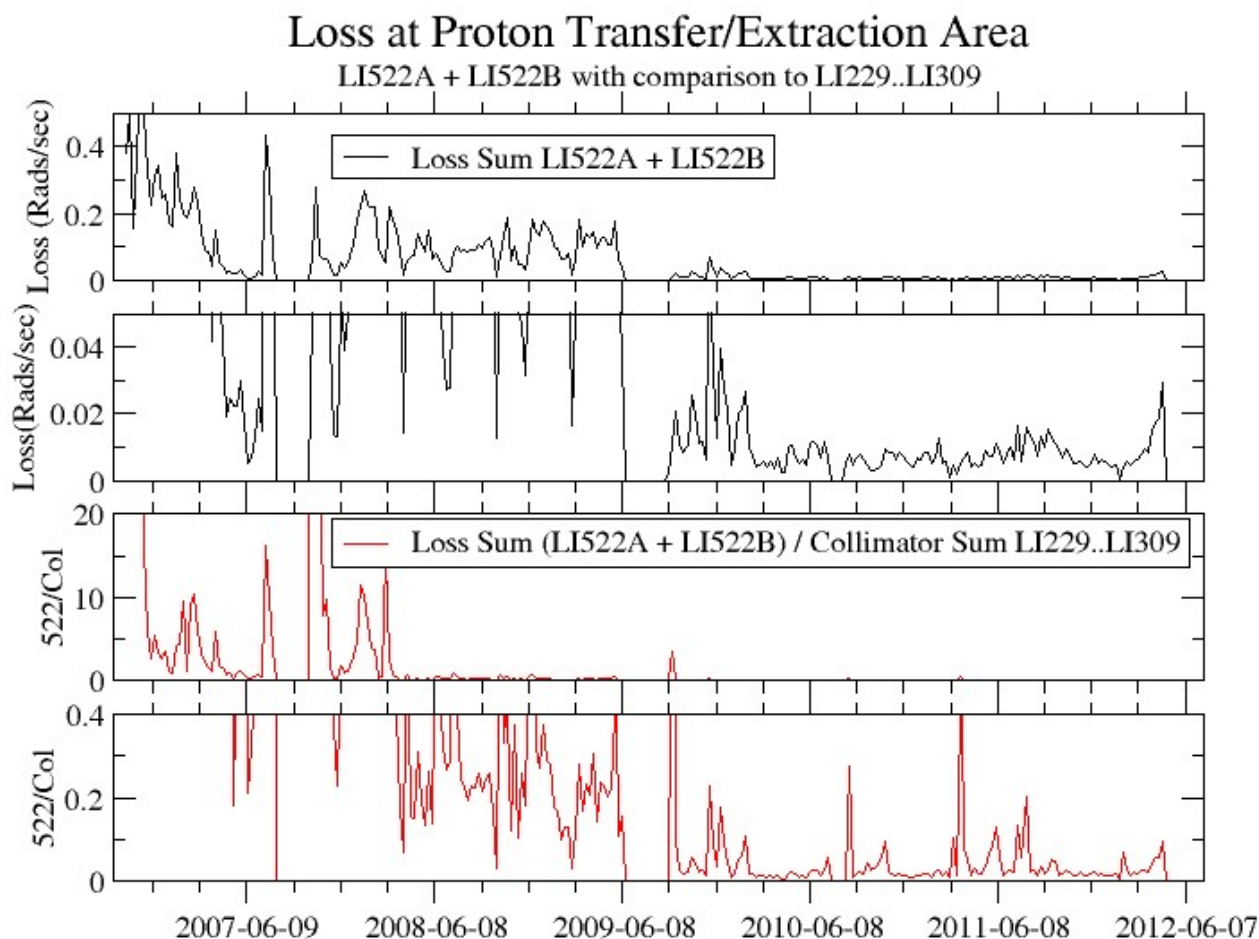


To evaluate the beam lost at the collimation region, we are to employ the difference between the beam injected (TOR852) and the beam delivered to the experiments (NuMI and PBar) but we need to account for the losses besides the collimator loss. This plot shows that between 10% and 20% of the loss was in the injection gap. We see that it was about 15% in the NuMI-only running from Fall 2011 - Spring 2012. It appears to be considerably lower in the January - June 2011 period when we had commissioned the GCK. However, one might be concerned that there is an accounting issue here.

We recognized (remembered) another accounting issue which is illustrated with the black line on this plot. For some period of time the Beam Budget Monitor (BBM) software had a timing problem which caused it to over-report TOR852 by about 3%. Using the BBM data without the correction in some other calculations seemed to result in inconsistent collimator BLM calibrations in some eras. To examine the issue we applied a uniform 3% decrease to TOR852 from the week of 9/7/2009 through 1/4/2010 and again from 12/6/2010 through 1/31/2011. It appears that this correction may be an overestimate, especially in Dec09--Jan10 whereas this plot suggests that the correction in Dec10/Jan11 makes a more consistent picture. To examine this with different data sources, we used D44 to plot M:TR105B/I:14SUM3 and E:TORTGT/I:19SUM3 for various weeks in the era with 3% over-counting of TOR852 by BBM. These plots show that the weeks selected for 3% correction were suitably chosen but the correction is not precise.

At this point we can conclude that the beam loss from the injection gap accounts for a variable fraction of the beam which is not delivered to the experiments ranging from 8% to 18% with an uncertainty of several percent. We will take this into account when fitting for the collimator region BLM calibration.

Residual Radiation at MI522 Lambertson



While examining the loss control issues for high intensity operation of the Main Injector, losses at the main transfer points were a major concern. These include MI40 - Abort, MI52(P150) - proton transfer to Tevatron and extraction for PBar and External Beam Switchyard, MI60 - NuMI Extraction and MI62(A150) - PBar transfer to Tevatron as well as the transfer to/from the Recycler at MI221 and MI322. Loss control eventually made these less important. Here we show the loss sums for two loss monitors near LAM522. LI522A received about 90% of the sum which is plotted. LI521B also received significant loss in this region but this plot will illustrate the important issues. The upper two plots show the weekly average BLM signal while the lower two plots compare this loss to the weekly average loss sum from LI229 through LI309. The two sets show the data on scales which differ by a factor of 10.

The improvements came in several steps. The commissioning of the new BLM electronics in October 2006 allowed the losses to be readily observed and subsequent tuning resulted in a huge improvement (see top graph in Fig. 14 of Ref [2]). Loss continued to drop for more than nine months. Following the 2007 shutdown (Oct 2007), we see the loss was about constant (top graph) from the end of the 2007 shutdown until the beginning of the 2009 shutdown (June 2009). When compared with the collimator loss (3rd plot) we see an apparent sudden drop when collimator commissioning achieved useful efficiency in Spring 2008 but this was due to an increase in the denominator. In the period from Fall 2008 through Fall 2009, this loss was 23% of the collimator loss as measured by the BLM. This dropped to 2.3% in the period from Fall 2009 through Fall 2010. This resulted from the successful removal of extraction gap beam using bunch-by-bunch dampers in anti-damping mode. The ratio remained in the range from 2.5% to 5% in the remaining operation through April 2012.

We will not try to subtract these losses when understanding the collimator region BLM's because the BLM signal is partly due to 8 GeV losses but significant signal is due to extraction loss at 120 GeV where each proton lost will deposit 15 times more energy and a roughly proportionate higher BLM signal. Instead, we will use this information to suggest when we might profit best in using transmission information to calibration the collimator losses. The changes in the loss were of

similar character at all of the transfer points. We will see that the collimator loss is a better match to the transmission information after the 2009 shutdown.

III. Residual Radiation at Secondary Collimators

The activation created by beam loss is the primary focus of our efforts. The BLM's show the losses in real time. We have measurements of the resulting residual activation in the tunnel including extensive measurements at bar-coded locations [4] from 2005-7 through the shutdown in 2012-3 and beyond. We have found that the activation is explained to modest accuracy by fitting the residual radiation at the bar coded locations to the half life weighted sums of the losses at nearby BLM's [4]. We also placed Al Tags at locations on the collimator near the bar code and studied the resulting activation of the Al by measuring the production of Na-22. We will employ these two data sets for calibrating the BLM results in terms of lost protons.

Al Tag Activation

The Al Tag activation study was reported in Beams-doc-3980 [5]. Results were employed for preliminary BLM calibrations in Beams-doc-4519 [1] and in the ARIA2015 paper [3]. Some results from Beams-doc-4519 will be repeated here for continuity of the discussion. Al Tag activation studies were carried out at 15 locations in the Main Injector collimation region. Four of these were on the aisle side near the longitudinal center and a bit above beam height on each of the secondary collimators. We conclude (see below) that almost all the primary protons which were collimated (scattered by the primary collimator) were lost into one of the secondary collimators. Residual radiation measured at the aisle face of the collimators (see next section) is due to activation products near the interaction point in the core of the secondary collimator which are produced by the interaction of these protons. That residual radiation will be therefore proportional to the protons lost in that collimator. Activation of the Al Tags at the secondary collimators is dominated by secondaries also produced by the protons lost at the design interaction point (end of the tapered section of the secondary collimator). But for C303 and C308, some of the shower of secondary particles from the C301 (for C303) and C307 (for C308) escapes the mask system and also activates the Al Tags (see Loss Localization section above). The BLM signal at the local loss monitor is also dominated by the local loss but the impact of upstream loss at LI303 and LI309 is even larger than that for the Al Tags.

Al Tags were placed prior to beam operation after the collimator installation in Fall 2007. They were removed at approximately one year intervals as follows:

Tags placed	10/12/2007	
Collected 1	10/8/2008	362 Days
Collected 2	8/26/2009	684 Days
Collected 3	8/12/2010	1035 Days

In addition, a 4th tag from C307 which was placed with the original set was removed on 12/20/2011.

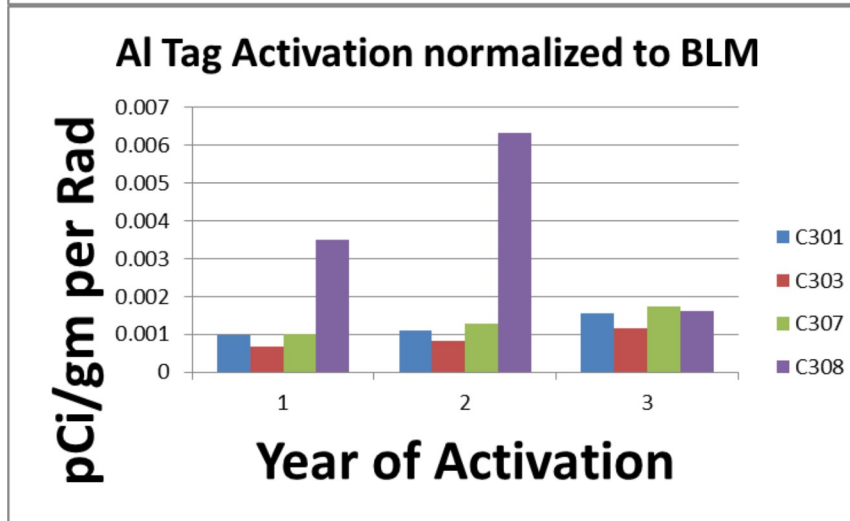
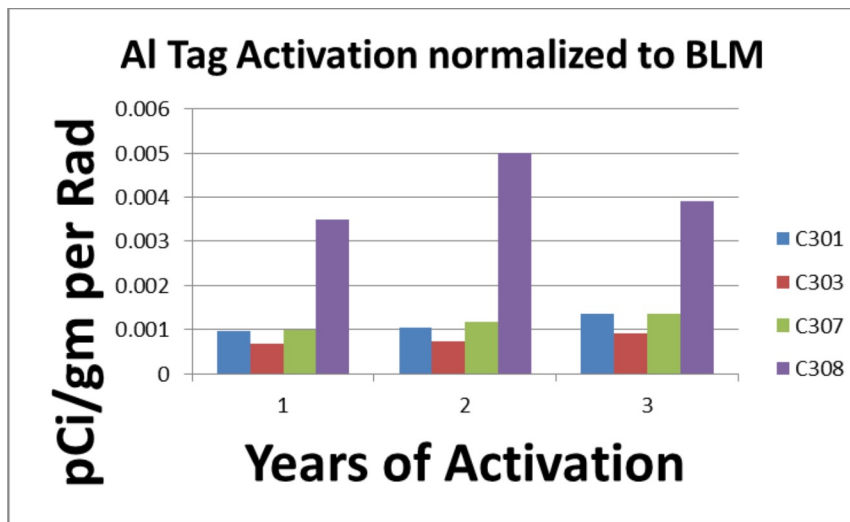


Table 3: Al Tag Calibrations - Sum over Years

Al Tag Loc.	BLM	Time	Activation	BLM
			pCi/gm	Rads
C301	LI301	10/8/2008	251.93	258874.96
		8/26/2009	540.34	523647.94
		8/12/2010	1812.31	1339301.17
C303	LI303	10/8/2008	849.31	1266726.38
		8/26/2009	1736.11	2381237.31
		8/12/2010	4137.32	4540779.73
C307	LI307	10/8/2008	360.97	363648.10
		8/26/2009	1232.10	1061289.74
		8/12/2010	2374.88	1761611.85
		12/20/2011	2834.06	2325746.91
C308	LI309	10/8/2008	1818.78	521118.06
		8/26/2009	6402.75	1278976.61
		8/12/2010	8304.09	2124588.01

Table 4: Al Tag Calibrations - By Year

Al Tag Loc.	BLM	Time	Activation	BLM	Act/BLM
			pCi/gm	Rads	PCi/gm/Rad
C301	LI301	Year 1	251.93	258874.96	0.000973
		Year 2	288.41	264773.9770	0.00111
		Year 3	1271.97	815653.24	0.00157
C303	LI303	Year 1	849.31	1266726.38	0.000670
		Year 2	886.81	1114510.92	0.000822
		Year 3	2401.20	2159542.43	0.001143
C307	LI307	Year 1	360.97	363648.10	0.000993
		Year 2	871.13	697641.64	0.00127
		Year 3	1142.78	700322.11	0.00175
		Year 4	459.18	564135.06	0.000814
C308	LI309	Year 1	1818.78	521118.06	0.00349
		Year 2	4583.97	757858.55	0.00633
		Year 3	1901.34	845611.40	0.00162

The decay correction for these measurements was modest but the available BLM history was used to make a detailed correction. For this reason, the ratio of activation/BLM signal in (pCi/gm) / (Rad) is calculated using the activation corrected for decay and the total measured BLM sum. Said in another way, we compare the produced activation to the total BLM signal for the same interval.

We compare the produced activation (pCi/gm) at the four collimator Al Tags to the unweighted BLM sum (Rads). This is the same ratio one obtains by comparing the measured activation to the BLM signal at each MI cycle weighted by the Na-22 half-life. The upper panel shows the result for the tags removed each year at each collimator. Since the tags at each location were co-located, we can get the yearly activation in year 1, 2 or 3 by subtracting the decay weighted Al Tag activation for tags removed after year 1, [year 2 - year 1], or [year 3 - year 2]. The excessive activation at C308 was created by secondary particles produced by the protons lost at C307. The failure to include masks to absorb the C307 out-scattered particles was rectified in the 2009 shutdown and in year 3, the activation rate for C308 Al Tags was similar to the rates observed at the other locations. We see that the activation rate normalized to the nearby BLM signal grows a little from year 1 through year 2 to year 3. We will use the rates at year 3 for calibrating the BLM to the protons lost.

Observation: If adjustments to collimation (collimator positions or time bump orbits) caused loss to be better contained in the secondary collimators, the BLM signal would be reduced and the ratio would be larger, as we observe.

Using the toroids, we can calculate the protons lost in year 3. We take TOR852 (injection), subtract TOR105B (for PBar) and TOR101 (for NuMI), then subtract losses from the Injection Gap as measured by the BLM's in 103..106 and TOR003

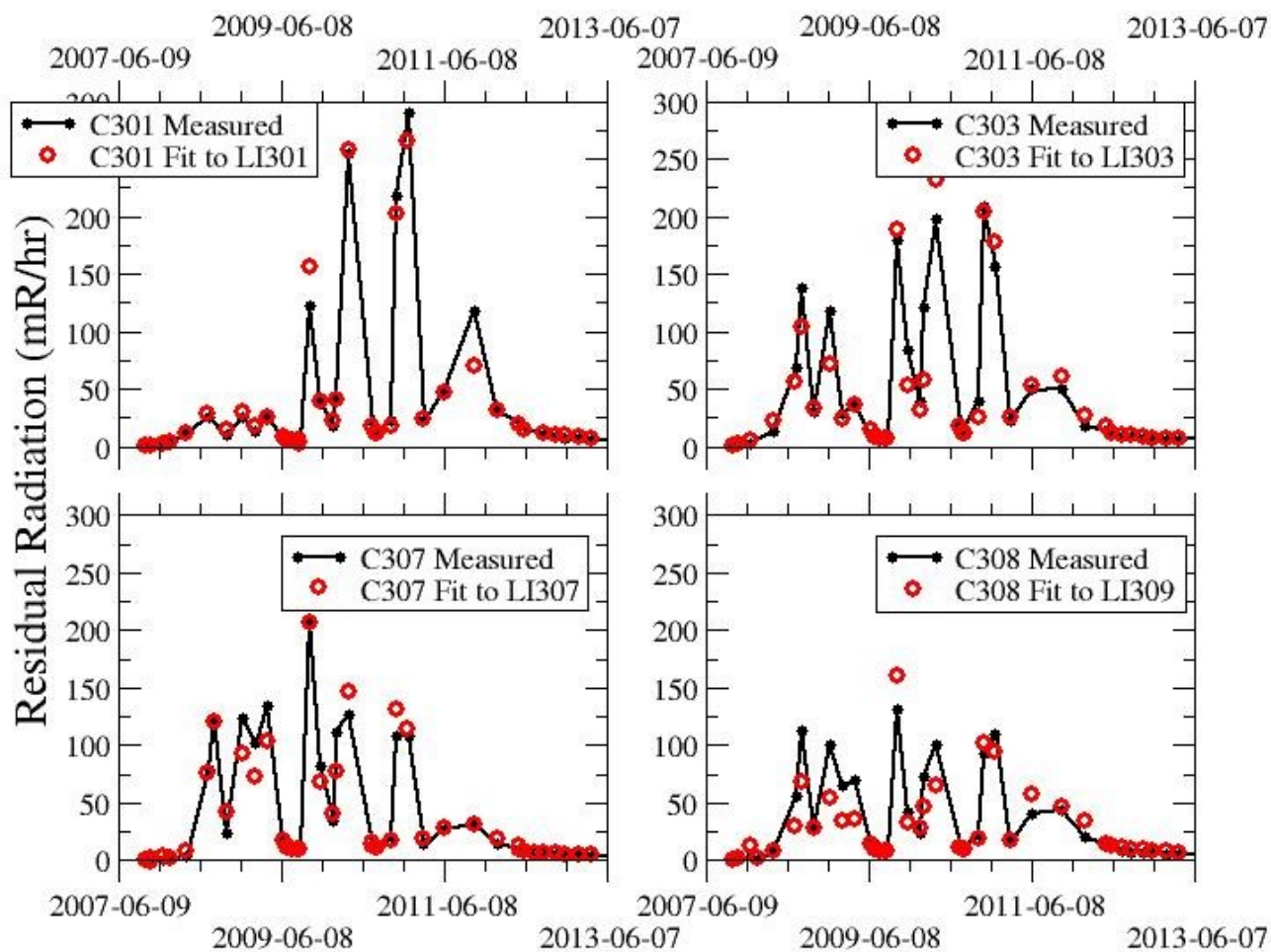
samples for the abort sample and the abort cleanup sample to obtain the weekly protons lost in the Main Injector. TOR003 samples for the Gap Clearing Kickers, are used for normalizing the Injection Gap loss as discussed above. As a reminder, the toroid data is obtained from Console Application I105 which displays data from the Beam Budget Monitor program. We find that in Year 3 there were $1.96328\text{E}+19$ protons lost.

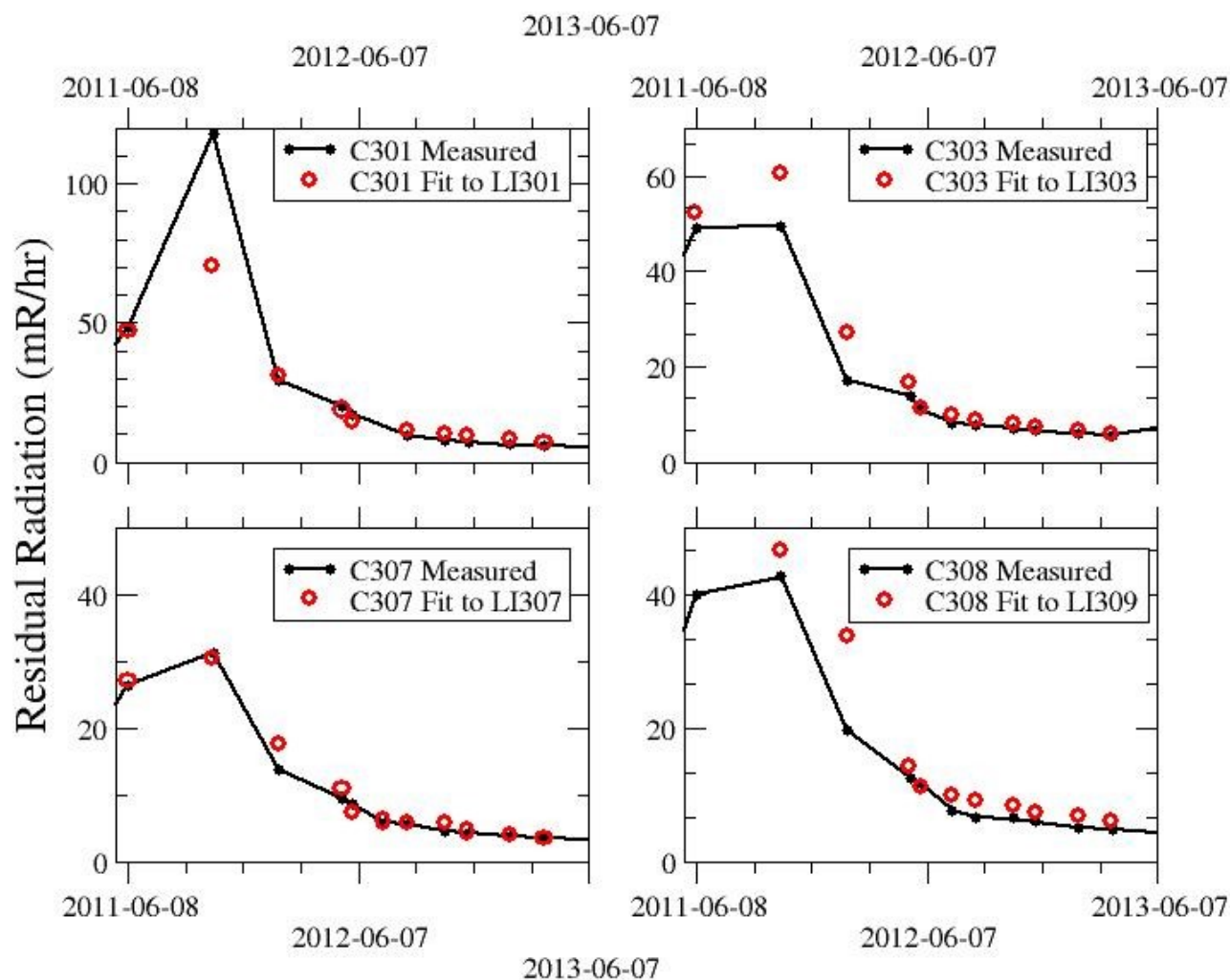
The sum of the corrected Al Tag Activation is 6717.28 pCi/gm for four collimator locations, When divided by the total proton loss between 8/26/2009 and 8/12/2010 we obtain $3.421\text{E}-16$ pCi/gm/proton. Applying this calibration and using the total BLM loss (in Rads) for the same period, a calibration for the four BLM locations is obtained. See these results in Table 5. Note that the loss at the primary collimator for this time period is neglected but is believed to be about 2%.

The data employed for this is shown in a Table 4. In the figure, we observe that the calibration for LI303 (red bar) is lower than for the other BLM's. We attribute this to a contribution to the LI303 signal from protons lost at C301. The match for LI309 is also not quite the same but this can be due both to the expected difference by geometry plus again a contribution for LI309 from protons interacting in C307.

Residual Radiation at Bar Codes on Collimators

In order to provide a well-documented set of residual radiation data, a set of bar-code tags were placed at selected locations and the residual radiation at those locations was recorded frequently [4]. It was shown that a simple linear regression analysis relating the measured residual radiation to sums of the weighted BLM loss on a nearby loss monitor using half lives of selected isotopes would describe the observed residual radiation [5]. See also more plots in [2].





These figures show fits using only the three isotopes Mn-54, Mn-52 and Mn-56. Fits with more isotopes are marginally more satisfactory but the limited data makes it difficult to constrain, for example, a fit which includes Fe-59 (44.5 day half life) or Cr-51 (27.7 day half life) and they will modify the coefficient for Mn-54. We choose to employ the component of residual radiation due to Mn-54 with a 312 day half life. One can employ fits for various time periods. Various fits show differences of up to about 10% in the coefficient for this term in the fit. Comparing the fits during long shutdown times we note a bias for the fit to fall above the measurement by a small amount. This is illustrated in the lower set of plots. We attribute this to failure to include a 27.7 day or 44.5 day component. The alternative of using the measured residual radiation at a specified time was considered and would give similar results at the 10% or so level.

For allocating the loss among the four collimators, one can do well with the three component fit using the Mn-54 component contribution and the integrated loss recorded by the appropriate BLM. To determine the fit coefficient, we select an I130 fit to the entire record from 2007 through 2013 of loss and residual radiation as shown. We choose the fitted coefficients as found in ColActFitsToBLM.xlsx or LossNTransmissionData.xlsx and calculate for three time periods (26-Aug-09 - 12-Aug-10; 12-Aug-10 - 30-Sep-11; 30-Sep-11 - 30-Apr-12) the activation produced (using the BLM integral unweighted). We sum this for the 4 collimators to get a total produced residual radiation for each period. The protons lost is summed for the same time period and the ratio provides a calibration of protons/mR/hr. This is the Mn-54 residual radiation produced by a proton lost in the secondary collimator. The average for the three time periods is 4.80×10^{17} protons per mR/hr. The calibration results are in agreement at the 1% level for the first two periods but for the last period it claims that 10% fewer protons can produce the same activation. Note that this is not actually comparing changes in activation (we would need to look at measured residuals or limited time fits for that) but reflects how well the BLM response sum matches the proton loss sum. One can see detailed comparisons among the three time periods in ColActFitsToBLM.xlsx.

To move forward to a calibration set, we use the BLM loss sensitivity from above and calculate a number of lost protons for each collimator/BLM combination and also the BLM residual radiation (in Rads) produced by that loss. The ratio of

those provide a calibration in Rads/proton or protons/Rad. The sensitivity calculated in the fashion is much higher for LI303 than for LI301 or LI307. The geometry for the collimators and loss monitors is nearly the same -- essentially identical for 303 and 307 while LM301 is a few inches further from C301 so that if the loss were at a point, the solid angle would be about 20% smaller. Using the average of the 301 and 307 results as the nominal sensitivity, and averaging this result for the first two of our three years (the ones which agree best with each other) we have a sensitivity to apply to as the calibration for LI301, LI307 and LI309. We also apply this sensitivity to LI230 as a nominal starting point. An attempt to attribute the remaining LI303 signal to C301 loss was not successful but by assuming twice the average(LI301,LI303) sensitivity as the LI303 sensitivity and assuming the remaining LI303 signal was due to C301 loss, we made progress. We similarly assigned LI309 the same sensitivity to LI308 losses as average(LI301,LI303) and assign the excess response of LI309 to loss at C307. This sensitivity matrix (Table 6) for Rads per proton was then inverted (MINVERSE function in Excel) to provide a sensitivity in protons/Rad. We chose to invert a 4x4 matrix and supply the correlation between CPH230 and LI230 as simply the inverse of the LI230 and CPH230 value. See Table 8 below for the numbers.

Calibration by Fit

In hopes of obtaining a better understanding of the BLM calibration, a fit scheme was devised to compare the weekly loss as measured by the toroids with the loss measured by the five loss monitors adjacent to the collimators. The injection gap loss was determined from the abort toroid on the Gap Clearing Kicker firing when available but this was supplemented by the loss measurement at LI103-106 since that was the available measurement prior to commissioning the GCK. For each week a proton loss from the BLM system was subtracted from the proton loss from the Toroid measurements. For an error term (denominator) we assumed a 1% error on each toroid measurement which is the nominal precision of the toroid calibrations (a systematic error). The 'ChiSum' was calculated by adding the square of the weekly proton difference divided by the square of this error term for the time period under consideration. While the uncertainty of the BLM signal is neglected and the random error in the toroid measurement is not accounted for, this does help in accounting for the sometimes large changes in the beam delivered to NuMI or PBar and also makes the weeks of low beam less important in the sum.

For the BLM protons lost, we started with the matrix obtained as above from the residual radiation calibration. Using the Excel Solver tool with the GRG nonlinear optimization, one can select one or more of the calibration values to optimize and seek the minimum 'ChiSum' for a selected time interval. The time intervals available were all weeks from October 2006 when the BLM data recording began to 30 April 2012 at the end of that era of NuMI operation. While fitting, values for 'ChiSum', ProtonDif, BBM Loss, BLM loss, Diff/LossBBM, |Diff/Loss| were displayed for the following intervals (no overlapping except the first and last): All, PreCol, Yr 1, Yr 2, Yr 3, EndTev, NuMI, GoodCol (Yr 2 to end). See Table 10 for the intervals and calculation results. Note that the preferred 'Simplex' optimization failed. Nevertheless, by strategically observing the result in all time periods and optimizing one, two, or occasionally three parameters for a selected time interval an improved match of the BLM and Toroid description of proton losses was obtained. Several fit iterations were employed. In preliminary efforts, the constraint of making the loss difference sum to zero or minimizing the absolute value of the loss difference was not helpful in finding a more satisfactory calibration.

Collimation optimization (orbit time bumps and collimator positions) was revised a number of times from 2008 through 2010 and then remained fairly static. But the loss pattern still had small changes. As a result, no wide range of different conditions was available to decouple the various parameters. However, in January 2009, in order to reduce loss at the K304 PBar transfer kicker, we made urgent changes which remained in place with little improvement until the shutdown in June 2009. While examining the BLM calibrations in the present study, we found that during this period, the loss at LI230 due to protons lost at the primary was about x10 higher than in other periods. It was only 2% in later periods but was about 25% of the loss in this time frame. With this in mind, we made preliminary fits to other parameters, then fit the Yr 2 time period for the sensitivity of LI230 only. The assigned sensitivity dropped from a previously assigned 6.73 Tp/Rad to 4.87 Tp/Rad. As further adjustments were made to other parameters, this ends up being only 40% different than LI301 sensitivity. Restated, this suggests that it takes 40% more protons lost to produce the same signal in LI301 as it does to make the signal at LI230 (shielding and some geometry differences).

The Calibration Numbers

To express the numbers compactly, let us describe them as matrices T and T^{-1} which relate vectors L (Rads) = (LI230, LI301, LI303, LI307, LI309) of BLM losses in Rads (integrated) to C (protons) = (C230, C301, C303, C307, C308) of protons lost. We say $L = T * C$ or $C = T^{-1} * L$. Calibrations using AI Tags were created for a diagonal matrix while the

Residual Radiation calibration introduced off-diagonal terms connecting loss at C301 to LI303 and loss at C307 to LI309. These terms were then re-determined using the fit.

Table 5: Calibration Matrix T using AI Tags

Rads/proton	C230	C301	C303	C307	C308
LI230	1.485E-13				
LI301		2.194E-13			
LI303			3.077E-13		
LI307				2.097E-13	
LI309					1.522E-13

Table 6: Calibration Matrix T using Residual Radiation

Rads/proton	C230	C301	C303	C307	C308
LI230	1.485E-13				
LI301		1.485E-13	1.110E-13		
LI303			2.948E-13		
LI307				1.485E-13	6.454E-14
LI309					1.485E-13

Table 7: Calibration Matrix T^{-1} using AI Tags

protons/Rad	LI230	LI301	LI303	LI307	LI309
C230	6.732E+12				
C301		4.558E+12			
C303			3.250E+12		
C307				4.769E+12	
C309					6.571E+12

Table 8: Calibration Matrix T^{-1} using Residual Radiation

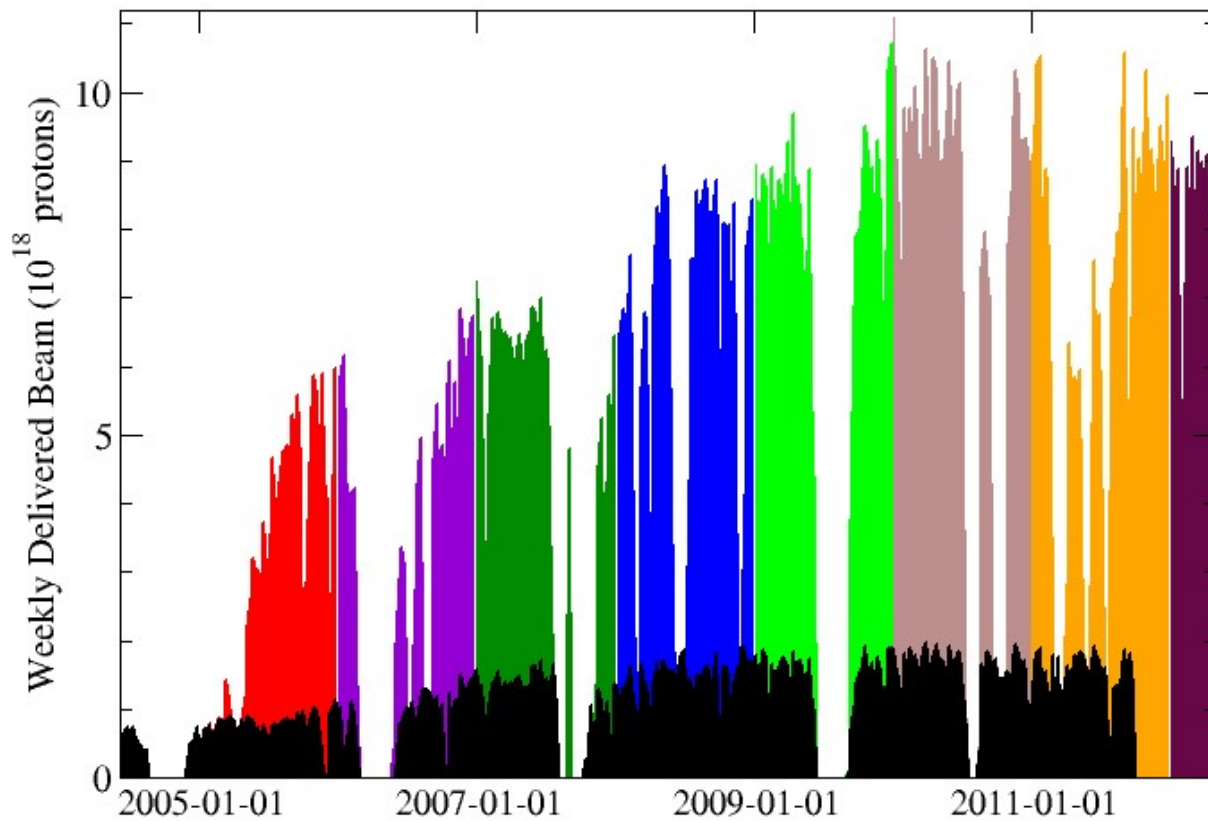
protons/Rad	LI230	LI301	LI303	LI307	LI309
C230	6.732E+12				
C301		6.732E+12			
C303		-2.535E+12	3.392E+12		
C307				6.732E+12	
C309				-2.925E+12	6.732E+12

Table 9: Calibration Matrix T^{-1} from Fit

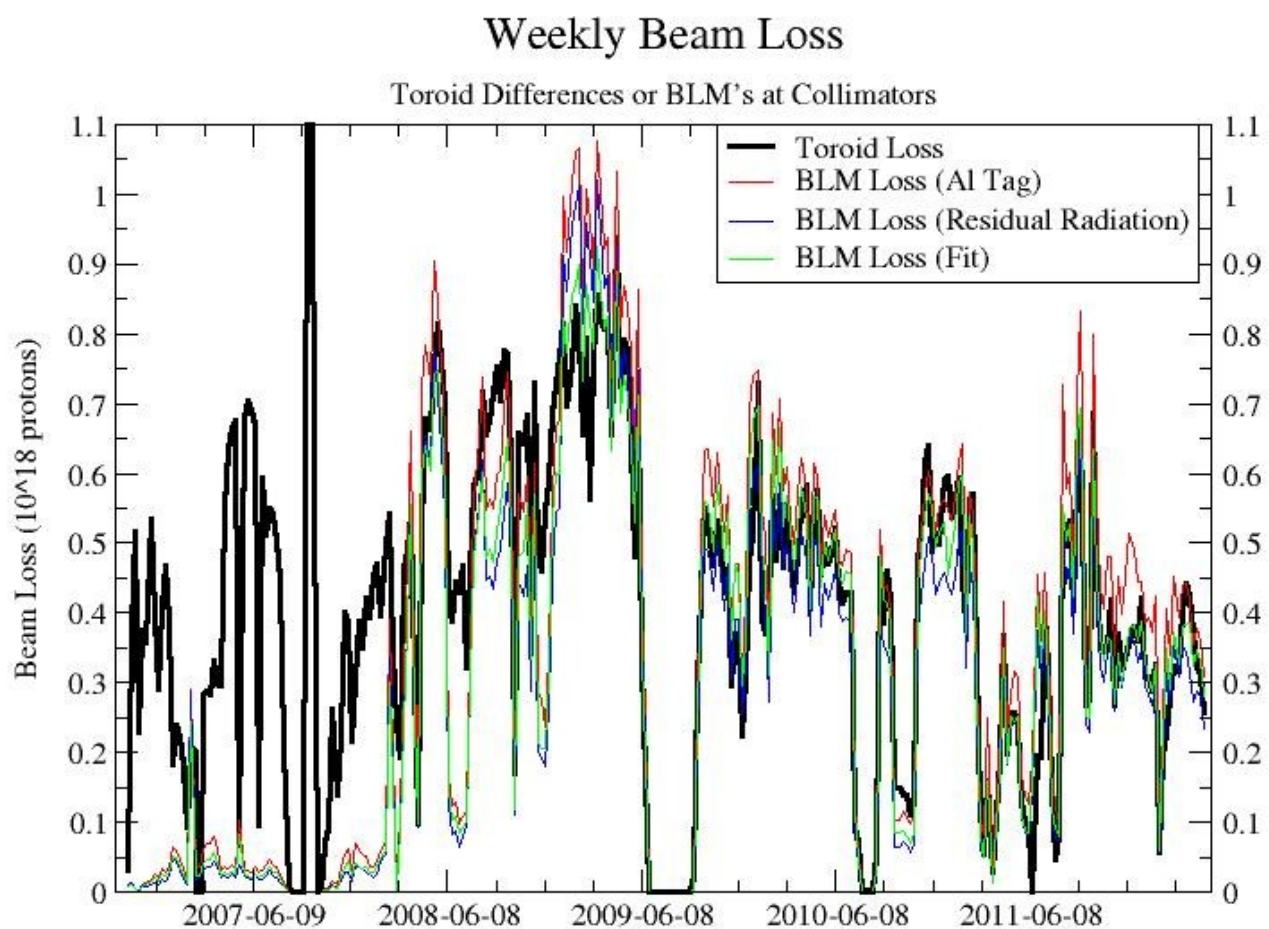
protons/Rad	LI230	LI301	LI303	LI307	LI309
C230	4.865E+12				
C301		5.213E+12			
C303		-2.562E+12	5.201E+12		
C307				9.279E+12	
C309				-2.86E+12	5.688E+12

From Protons Accelerated to Loss and Loss Uncertainty

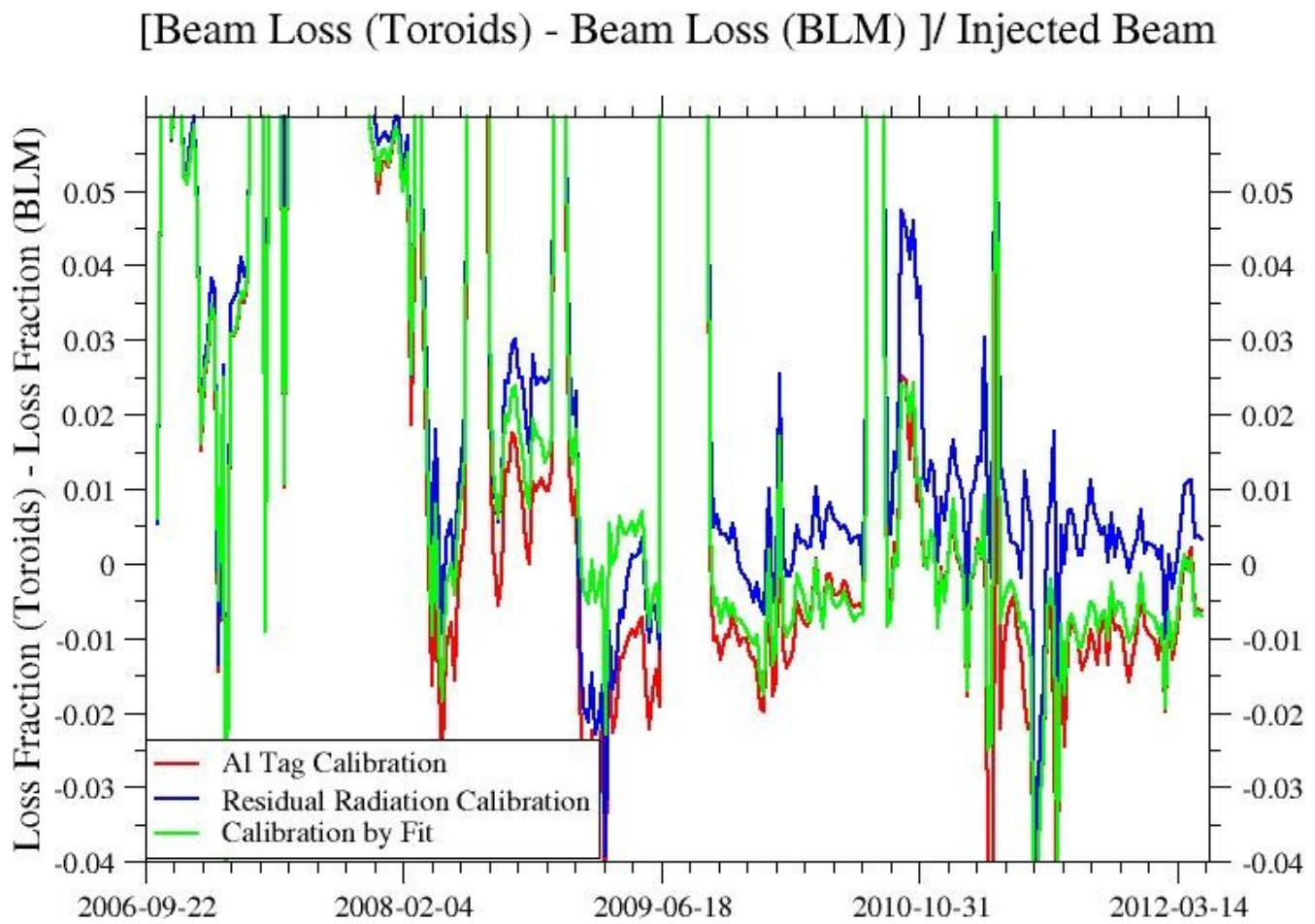
The total beam delivered to the experiments was presented in Ref [2] as shown in the next figure. It covers a longer time period since we were providing both PBar and NuMI targets with beam before the improved BLM electronics was available and before the collimation system was installed. The reader is encouraged to observe the appropriate time boundaries to see the various types of progress in loss control.



Unsurprisingly, the beam loss rose along with the beam delivered as we commissioned the slip stacking for PBar and then also for NuMI. The losses at the collimators as recorded by the BLM sum (at the collimators) rose through the collimation commissioning and up to the 2009 shutdown. As the loss control with anti-damping and GCK became more effective, the total loss as measured by either the toroids or the BLM system went down despite the rise in beam intensity. The lower weekly loss in early 2011 was largely due to less beam being delivered while the lower loss in the last 6 months of running was largely due to lower per pulse intensity in response to limits for the NuMI target.



We compare the loss measured by the toroids to various calibrations of the loss measured by the collimator BLM system. We present it normalized to the injected beam, finding that differences are about 1% of the injected beam. In the next plot we normalize to the loss as measured by the toroid and find that for most periods, the differences are about 10% of the loss. The differences in different operational eras emphasize that things did change and none of this is ideal.



Compare Loss from Toroid to BLM Measured Loss

Normalize to Toroid Loss

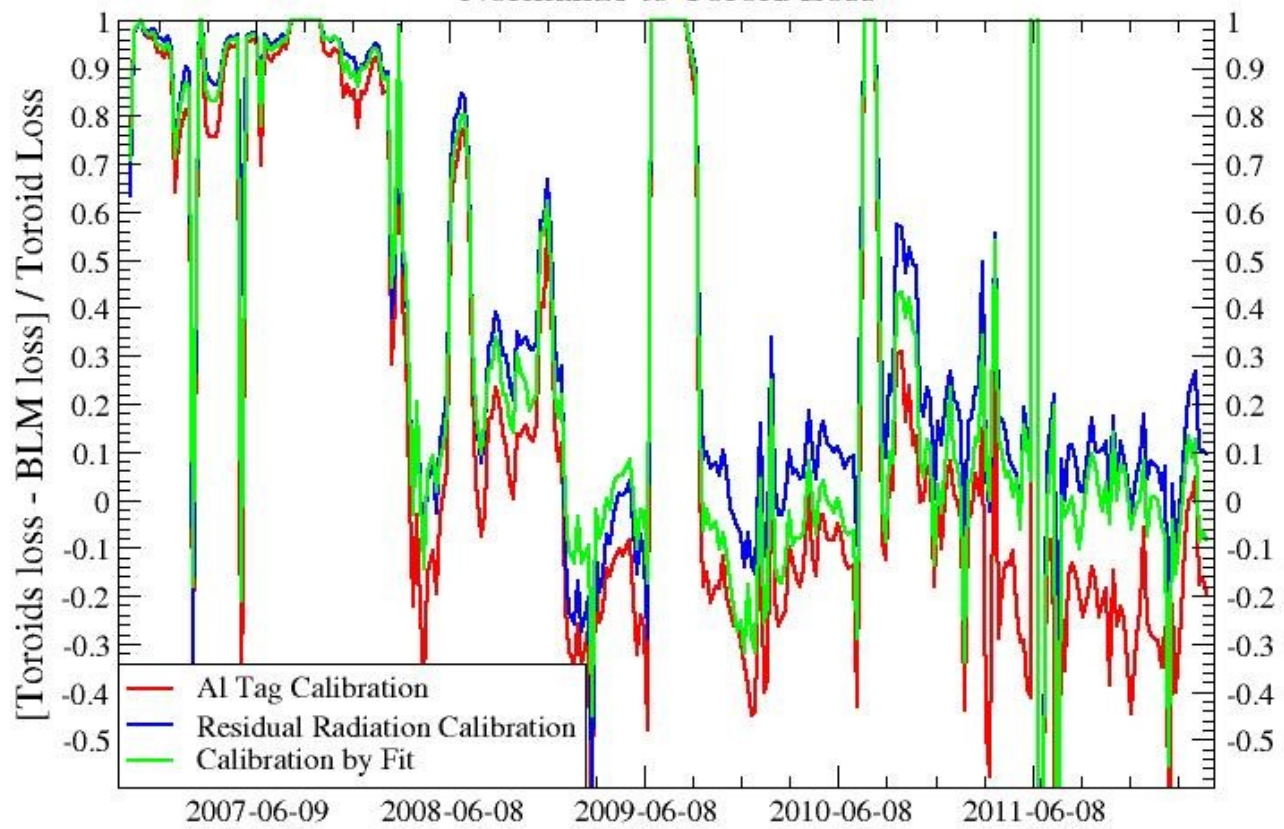


Table 10 details the results which were examined during the fit for collimator calibration. 'Solver' minimized a selected ChiSum for the row identified by the dates. The values of one or more cells which correspond to Table 9 were adjusted to achieve that minimum. But all the values were presented so that one could move around to examine different time periods and different fit parameters. The results for EndTev and NuMI time periods are very satisfactory as is the GoodCol which claims a satisfactory result for the whole time period after 26-Aug-09 when the collimation system optimization was completed.

Table 10: Fitting Results

Start	End	Label	ChiSum	ProtonDif	BBM Loss	BLM loss	Diff/LossBBM
12-Oct-07	30-Apr-12	All	2887.84	1.05E+19	9.70E+19	8.64542E+19	0.1082
9-Oct-06	12-Oct-07	PreCol	1554.38	1.44E+19	1.93E+19	1.37984E+18	0.7472
12-Oct-07	15-Oct-08	Yr 1	2287.65	1.00E+19	2.40E+19	1.39946E+19	0.4177
8-Oct-08	26-Aug-09	Yr 2	340.406	1.59E+18	2.37E+19	2.21279E+1	0.0670
21-Sep-09	12-Aug-10	Yr 3	14.9922	-1.56E+18	1.96E+19	2.11638E+19	-0.0795
12-Aug-10	30-Sep-11	EndTev	138.240	4.31E+17	1.97E+19	1.92397E+19	0.0219
30-Sep-11	30-Apr-12	NuMI	2.25120	2.39E+16	1.06E+19	1.05601E+19	0.0023
26-Aug-09	30-Apr-12	GoodCol	600.192	4.57E+17	7.29E+19	7.24596E+19	0.0063

Some discussion

It is fruitful to review some history of this study and make comparisons. Back in 2008, an examination of a single pulse loss was the first attempt to determine loss monitor sensitivity. Using the total loss in all loss monitors and the total beam loss determined by the DCCT, we observed 0.664 Rads/Tp or 1.506 Tp/Rad. This sensitivity is for the response to both protons and the secondary radiation they produce. Let us apply the factor of x2.35 for total response over local response (see below) and we would assign a response of 3.54 Tp/Rad. We obtained a response from a one pulse measurement of loss for uncaptured beam in Spreadsheet pfl-11JUN13-143510-amc01_20140115.xlsx as saved in Beams-doc-4519. There are response of the secondary collimator BLM added to 4.14 Tp/Rad or 0.242 Rads/Tp.

In our discussions above, we have shown that the local loss at LI113 was about 0.33 to 0.37 of the sum LI113..LI116. We infer that the total BLM response is from x3 to x3.7 of the signal at the proton loss point. For the response in the collimator region, we have Col = Sum(LI229..LI309) to compare with Sum(LI301, LI303, LI307, LI309) which we compare for the interval from Yr 3 to the end (8/26/2009 to 3/30/2012). We find the ratio of 0.426 so the total response is x2.35 of the local proton loss response.

We should also comment on the difference between the results in this document compared with Beams-doc-4519 [1]. Table 4 of that document reported a response x1.38 higher than in Table 7 above. This is due to a different proton loss computation. In this work we correctly accounted for Abort loss (aborts and 'clean-up') and for the injection loss as measured by losses at LI103-LI106 in this time interval. In addition, the assumption here that the BBM program over-counted the injection beam by 3% for part of Yr 3 changes reduces the proton loss by 17%. The overall difference between the AI Tag results in Table 7 and in Beams-doc-4519 Table 4 is 38%.

If we average the sensitivities reported in the above tables, we find the AI Tags give 5.17 Tp/Rad (Table 7) while the Residual Radiation (Table 8) and the Fit (Table 9) give 3.55 Tp/Rad for a ratio of 1.456 or 46% higher reported response.

Summary and Conclusions

The issues we know about concerning data logger and Beam Budget Monitor bookkeeping lapses have forced us to do the many cross checks discussed in this work. We believe that we can use the corrected loss as measured by the toroids with reasonable assurance that we have control of the uncertainties. Beam measurements with the DCCT are useful but the slow response requires one to avoid the very early times so injection losses are not well determined. Some eras are better than others for some of the activation studies we will be doing. It appears that our AI Tag study for Year 3 corresponds to reasonable toroid measurements of the loss but only after the ad hoc 3% correction. Perhaps the final operation period from September 2011 through April 2012 is well-suited for studies using the bar-coded tag residual radiation. Since the Mn-54 results are nicely determined in the 2013-13 shutdown, we can expect that we have a good measure of the loss which created the activation.

We will apply these results for making comparisons with the MARS simulations. MARS calculated results for AI Tags, BLM response and Residual Radiation. The proton losses which created the measured results can be used to normalize properly the MARS and measurement results.

Final Comments

Several Excel spreadsheets which were used in this work will be 'safeguarded' by including them in the BeamsDocDB location for this work. Initially, it was attempted to make them sufficiently well-organized as to allow others to see their logic. It is likely that a reader can find much useful data and some useful calculations in these spreadsheets but the author apologizes for the final disorder. It might be helpful to at least know that the initial fit effort used one worksheet for summing while the final results were in an entirely different worksheet.

References

- [1] Bruce C. Brown, "Studies of MI Beam Intensity, Loss and Activation Patterns", [Beams-doc-4519-v1](#), 28 Jan 2014.
- [2] Bruce C. Brown et al., "The Fermilab Main Injector: high intensity operation and beam loss control", [DOI](#), Phys. Rev. ST Accel. Beams 16, 071001, 9 July 2013.
- [3] Bruce C. Brown, "Relating Beam Loss, Activation and Residual Radiation for 400 kW Operation of the Fermilab Main Injector", ARIA2015, Knoxville, TX, 15-17 April 2015.
- [4] Bruce C. Brown, "Residual Radiation Monitoring in the Main Injector with the ROTEM RAM DA3-2000 Radiation Survey Meter", [Beams-doc-3523-v1](#) 16 Dec 2009.
- [5] Bruce C. Brown and Guan Hong Wu, "[Measuring Correlations Between Beam Loss and Residual Radiation in the Fermilab Main Injector](#)", Proceedings of the 46th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB2010), P. 391-394, Also available as FERMILAB-CONF-10-368-AD.
- [6] Bruce C. Brown, "Analysis Procedures for AI Activation Studies", [Beam-doc-3980-v2](#), 09 Apr 2012.